A 2D auxetikos system based on interconnected shurikens

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Abstract

A 2D material that expands biaxially upon thermal change, regardless of whether the temperature increases or decreases, is introduced herein. To do so, it must possess an overall conventional or positive thermal expansion under the influence of heating, but the coefficient of thermal expansion must switch to a negative value upon cooling. A novel microstructure is proposed herein in the form of interconnected shuriken network, whereby each rigid shuriken is connected to four connecting rods via four pairs of rotating rods. All rods contract during cooling but the swiveling of the rotating rod produces a net increase of the unit cell expansion in spite of the connecting rod contraction, thereby leading to an overall negative thermal expansion. During heating, the rotating rods are made redundant through the action of an interlocking mechanism while the connecting rods expand, thereby resulting in an overall positive thermal expansion. The capability for the material system to flip the sign of its thermal expansivity paves a way for engineers to design material systems that possess opposing properties in order to respond in a consistent manner in spite of opposing stimuli.

Keywords 2D materials · Auxetikos · Network · Shurikens

List of symbols

l_c	Half-length of connecting rod
l_r	Length of rotating rod
l_s	Half-length between sharp edges of shuriken
T	Temperature
x	Half-length of unit cell dimension measured along the x-axis
x_0	Original half-length of unit cell dimension measured along the x-axis

Greek symbols

α_c	Coefficient of thermal expansion (CTE) of connecting rod
α_r	Coefficient of thermal expansion (CTE) of rotating rod
α_x	Coefficient of thermal expansion (CTE) of unit cell in x-direction
ε	Strain
ν	Poisson's ratio
σ	Stress
θ	Half-angle of shuriken corner

Sub-scripts

eff	Effective property
x	x-direction
y	y-direction

1 Introduction

From the Greek work αὔξις (auxesis), a noun meaning “increase”, comes the word αὐξητικός (auxetikos), which means “that which tends to increase”; the latter leads to the term “auxetics”, which has been coined for referring to materials and structures that exhibit negative Poisson's ratio [1]. Due to the exponential increase in the research activities on auxetic materials and systems in recent years, it is no longer possible to provide a comprehensive list of auxetics literature; the reader is therefore referred to comprehensive reviews [2–15] and two monographs [16, 17] in the field of auxetics. While the introduction of auxetic materials paves a way for designing materials for structural applications in which it is advantageous to possess

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negative Poisson's ratio, there are also other structural applications where it is advantageous to possess positive Poisson's ratio. In cases where both conditions take place, it is prudent for such materials and structures to be able to possess both positive and negative Poisson's ratio, depending on the loading condition. A preliminary design on such system has been attempted, in which the sign of Poisson's ratio switches between positive and negative values in situ, in response to the change in stress direction, e.g. $\nu_{xy} > 0$ when $\sigma_{xx} > 0$, but the Poisson's ratio sign switches to $\nu_{xy} < 0$ when $\sigma_{xx} < 0$, thereby always giving $\varepsilon_{yy} < 0$ regardless of whether σ_{xx} is tensile or compressive [18]. Following that, an attempt was made to explore the possibility in auto-locking of fibers onto their surrounding matrix materials, i.e. the radial dimension tends to increase regardless of whether the fiber is being pulled or being pushed, so as to prevent being displaced axially. By means of microstructural duality, each microstructure can be made to manifest two distinct effective microstructures such that $\nu_{xy} < 0$ when $\sigma_{xx} > 0$, but the Poisson's ratio sign toggles to $\nu_{xy} > 0$ when $\sigma_{xx} < 0$, thereby always giving $\varepsilon_{yy} > 0$ regardless of whether σ_{xx} is tensile or compressive [19], i.e. the dimension that is lateral to the stress application *tends to increase*, thereby indicating auxetikos behavior transverse to the load line. Having shown the capability of materials to exhibit Poisson's ratio sign switching upon stress direction reversal, it has recently been proven that the coefficient of thermal expansion (CTE) sign can be switched between positive and negative values in situ, in response to thermal fluctuation, specifically $\alpha_{eff} > 0$ when $dT < 0$, but the effective CTE sign flips to $\alpha_{eff} < 0$ when $dT > 0$, thereby always giving negative thermal strain $\varepsilon < 0$ regardless of whether the temperature increases or decreases [20], which is not auxetikos. Recently a class of metamaterial consisting of rectangular cells in triangular array has been conceptualized using alternating bimerials that are joined to the ends of cross beams, whereby the direction parallel to the cross beams can be designed to be positive thermal expansion (PTE) or negative thermal expansion (NTE) while the direction parallel to the bimerials always give negative thermal strain [21]—again, such a system is not auxetikos. A follow-up work on a 2D microstructure was then made by aligning the alternating bimaterial strips parallel to both axes to form rectangular cells. These cells are arranged in rectangular array and are interconnected by cross beams oriented along both axes to give in-plane PTE, NTE, thermal shearing or zero thermal expansion (ZTE) [22]. As before, such a system is not auxetikos. A graphical description that shows how the present auxetikos system relates with positive thermal expansion (PTE) and negative thermal expansion (NTE) systems is illustrated in Fig. 1. For a temperature change of dT , recall that the thermal strain is defined as [23–25]

$$\varepsilon = \alpha dT, \quad (1)$$

where the proportionality constant α is the CTE [23–25].

It follows that under a thermal fluctuation with time t as shown in Fig. 1a, the conventional response in terms of thermal strain is shown in Fig. 1b in which the positive slope of the thermal strain versus temperature change plot indicates positive CTE $\alpha > 0$, i.e.

$$\left. \begin{array}{l} \varepsilon > 0 \Leftarrow dT > 0 \\ \varepsilon < 0 \Leftarrow dT < 0 \end{array} \right\} \Rightarrow \alpha = \frac{\varepsilon}{dT} > 0 \quad (2)$$

If, however, the material responds in the manner shown in Fig. 1c, i.e. the sign of the thermal strain always opposes the sign of the temperature change, then the corresponding negative slope of the thermal strain versus temperature change plot indicates negative CTE $\alpha < 0$, i.e.

$$\left. \begin{array}{l} \varepsilon < 0 \Leftarrow dT > 0 \\ \varepsilon > 0 \Leftarrow dT < 0 \end{array} \right\} \Rightarrow \alpha = \frac{\varepsilon}{dT} < 0 \quad (3)$$

Suppose the material behaves in the manner described in Fig. 1d, whereby the thermal strain is non-negative, then the CTE sign toggles between positive and negative depending on how the temperature changes; specifically,

$$\varepsilon > 0 \Leftarrow \begin{cases} dT > 0 \Rightarrow \alpha = \varepsilon/dT > 0 \\ dT < 0 \Rightarrow \alpha = \varepsilon/dT < 0 \end{cases} \quad (4)$$

Note that the thermal strain for auxetikos system is always positive to indicate it having the tendency to increase in dimension. This characteristic translates into two distinct slopes of the plot of thermal strain versus temperature, and the corresponding abrupt change in CTE at the original state. There has been no precedence whereby any material system expands based on temperature change magnitude, and therefore the auxetikos system considered herein is being presented for the first time.

In this paper, we attempt the development of a 2D auxetikos material system that tends to increase in dimension under both heating and cooling effect, i.e. $\alpha_x = \alpha_y > 0$ when $dT > 0$, but the effective CTE sign changes to $\alpha_x = \alpha_y < 0$ when $dT < 0$. The implementation of alternating CTE sign with thermal fluctuation is attained herein by incorporating a set of rotating rods that are redundant during heating but functional during cooling. These are indicated as inclined linkages that are parallel to the shuriken sides in the original state illustrated in Fig. 2a, while each shuriken is connected to its four closest neighbors by the horizontally and vertically aligned connecting rods. Upon cooling, all rods contract such that the hinges at the corners move away from the shuriken to a greater extent than the shortening of the connecting rods (Fig. 2, left), thereby creating an overall distancing between the shurikens. This translates to effective NTE behavior during cooling. Upon heating, only the connecting rods elongate (Fig. 2, right); the rotating

Fig. 1 For a given **a** temperature variation with time, the responses for thermal strain with reference to time (left column), thermal strain with temperature (middle column) and CTE with temperature (right column) are illustrated for **b** positive thermal expansion, **c** negative thermal expansion, and **d** auxetikus systems

rods encounter build-up of compressive thermal stress as the hinges are locked at the shuriken corners. For this reason, the next section on analysis consists of two parts for catering to two different overall expansion mechanisms.

2 Analysis

We consider a network of interconnected shuriken whereby every shuriken possesses four axes of symmetry, i.e. two axes of symmetry with each axis passing through the opposing sharp edges, and two axes of symmetry with each axis of symmetry passing through the opposing corners. Figure 3a shows a unit cell of the interconnected shuriken network, where the rotating rods and connecting rods in the original state are indicated by purple color, forming an angle of θ between them. The rotating rod is of length l_r while the entire connecting rod is of length $2l_c$ for connecting two shurikens. The half-length of each connecting rod l_c is therefore assigned to each connecting rod within the boundary of the unit cell. The horizontal

and vertical distances between neighboring hinges on the sharp edges within each shuriken is $2l_s$, so that its half-length

$$l_s = l_r \sin \theta \quad (5)$$

can be expressed by the rotating rod length and its angle formed with the connecting rod. Upon an increase in temperature of dT , the half-length of each connecting rod increases by

$$dl_c = l_c \alpha_c dT \quad (6)$$

where α_c is the coefficient of thermal expansion (CTE) of the connecting rod. However, there is no increase in the length of the rotating rods, as they are locked in place by the corners, thereby resulting in a build-up of compressive thermal stress. Suppose the origin of the coordinate system is placed at the center of the shuriken, the half-lengths of the unit cells as measured along the x-axis in the original state is

$$x_0 = l_s - l_r \cos \theta + l_c \quad (7)$$

while the same half-length upon heating is

Fig. 2 Schematics of 3-by-3 interconnected shuriken network under cooling (left) and heating (right) at **a** original state, **b** 5% rod strain magnitudes and **c** 10% rod strain magnitudes. Green squares indicate original size of 3-by-3 unit cells for comparison

$$x = l_s - l_r \cos \theta + l_c(1 + \alpha_c dT) \quad (8)$$

upon considering Eq. (6). If, in addition to the four axes of symmetry imposed on the shuriken we let $y_0 = x_0$ to give square array, then the in-plane strain is equibiaxial. Substituting Eq. (5) into Eqs. (7) and (8) gives the thermal strain in x-direction $\epsilon_x = (x - x_0)/x_0$ as

$$\epsilon_x = \alpha_c dT \frac{\frac{l_c}{l_r}}{\sin \theta - \cos \theta + \frac{l_c}{l_r}} \quad (9)$$

upon heating.

Upon a decrease in temperature, the half-length of the connecting rod changes by the amount indicated in Eq. (6), but this value is negative because $dT < 0$. Likewise, the change in the length of the rotating rod

$$dl_r = l_r \alpha_r dT, \quad (10)$$

where α_r is the CTE of the rotating rod, takes on a negative value for the same reason. Due to the contraction of the rotating rod, its angle formed with the connecting rod increases to $\theta + d\theta$, as shown in Fig. 3b. For these changes in rod lengths and angles, we have the updated half-length of the unit cell in x-direction

$$x = l_s - l_r(1 + \alpha_r dT) \cos(\theta + d\theta) + l_c(1 + \alpha_c dT). \quad (11)$$

Substituting $\cos d\theta = 1$ and $\sin d\theta = d\theta$ as $d\theta \rightarrow 0$ for infinitesimal deformation, we have

$$x = l_s - l_r(1 + \alpha_r dT)[\cos \theta - d\theta \sin \theta] + l_c(1 + \alpha_c dT). \quad (12)$$

The angular change can be eliminated by equating the vertical components of the rotating rod before and after cooling

$$l_r \sin \theta = l_r(1 + \alpha_r dT) \sin(\theta + d\theta) \quad (13)$$

to give

$$\frac{1}{1 + \alpha_r dT} = \cos d\theta + \frac{\sin d\theta}{\tan \theta}. \quad (14)$$

Considering infinitesimal deformation again, we have

Fig. 3 A unit of the shuriken network **a** in original state indicated by purple rods and extension of connecting rods by dl_c indicated in red upon heating, and **b** contraction of all rods upon cooling indicated in blue, where dl_r and dl_c take on negative values

$$d\theta = \left(\frac{1}{1 + \alpha_r dT} - 1 \right) \tan \theta \quad (15)$$

which, upon substitution into Eq. (12) gives rise to

$$x = l_s - l_r(1 + \alpha_r dT) \left[\cos \theta - \sin \theta \tan \theta \left(\frac{1}{1 + \alpha_r dT} - 1 \right) \right] + l_c(1 + \alpha_c dT). \quad (16)$$

Using Eq. (5) and recalling the original dimension described by Eq. (7), one obtains the thermal strain

$$\varepsilon_x = -\alpha_r dT \frac{\sin \theta \tan \theta + \cos \theta - \frac{l_c}{l_r} \frac{\alpha_c}{\alpha_r}}{\sin \theta - \cos \theta + \frac{l_c}{l_r}} \quad (17)$$

upon cooling.

From the definition of CTE $\alpha = \varepsilon/dT$, one can obtain the effective CTE of the interconnected shuriken network from Eqs. (9) and (17) for heating and cooling, respectively. When normalized against the CTE of the rotating rods, we have the dimensionless effective CTE

$$\frac{\alpha_x}{\alpha_r} = \frac{\frac{l_c}{l_r} \frac{\alpha_c}{\alpha_r}}{\sin \theta - \cos \theta + \frac{l_c}{l_r}}; \quad dT > 0 \quad (18)$$

for heating, and

$$\frac{\alpha_x}{\alpha_r} = -\frac{\sin \theta \tan \theta + \cos \theta - \frac{l_c}{l_r} \frac{\alpha_c}{\alpha_r}}{\sin \theta - \cos \theta + \frac{l_c}{l_r}}; \quad dT < 0 \quad (19)$$

for cooling.

3 Results and discussion

Effects from the various geometrical and mechanical properties of the interconnected shuriken network are investigated for rotating rod CTE of $\alpha_r = 20 \times 10^{-6} \text{ K}^{-1}$, connecting-to-rotating rod length ratio of $l_c/l_r = 1$ and the angle of $\theta = 60^\circ$ between these two rods. This choice of α_r is representative of typical metals with high CTEs, such as aluminum ($\alpha_{Al} = 23.1 \times 10^{-6} \text{ K}^{-1}$), brass ($\alpha_{Br} = 19 \times 10^{-6} \text{ K}^{-1}$), and copper ($\alpha_{Cu} = 17 \times 10^{-6} \text{ K}^{-1}$), which gives an average of $(\alpha_{Al} + \alpha_{Br} + \alpha_{Cu})/3 = 19.7 \times 10^{-6} \text{ K}^{-1} \approx 20 \times 10^{-6} \text{ K}^{-1}$. The effective thermal strains in x-direction ε_x are plotted in Fig. 4 (left side) while the corresponding effective CTEs in the same direction are furnished in Fig. 4 (right side) with reference to the change in temperature dT . Here, effects of the connecting rod CTE α_c is shown in Fig. 4a using rod

CTE ratio of $\alpha_c/\alpha_r = 0, 0.25, 0.5, 0.75$ and 1 . In deciding the range of α_c/α_r ratio, we begin with the premise that the both types of rods possess non-negative CTEs due to the

rarity of intrinsically NTE materials. While the attainment of positive thermal strain during heating is easily achieved solely by the expansion of the connecting rod arising from

Fig. 4 Plots of thermal strain (left) and effective CTE (right) against thermal change for various **a** connecting-to-rotating rod CTE ratio, **b** rotating-to-connecting rod angles, and **c** connecting-to-rotating rod length ratio

the prevention of rotating rod expansion due to the locking effect, as indicated in Fig. 3a, we note from Fig. 3b that the displacement of the rotating-to-connecting rod hinge must be greater than the shortening of the connecting rod in order to achieve positive thermal strain upon cooling. As such, we identify the range $0 \leq \alpha_c/\alpha_r \leq 1$ as being reasonable with increments of 0.25 to produce five sets of data. Influence from the connecting-to-rotating rod subtending angle is furnished in Fig. 4b for $\theta = 50^\circ, 55^\circ, 60^\circ, 65^\circ$ and 70° . In determining the range of θ ratio, we note that from Fig. 3 that $45^\circ < \theta < 90^\circ$ by geometrical reason. A central value of $\theta = 60^\circ$ was chosen as it would give convenient trigonometric expressions. Hence a range of $50^\circ \leq \theta \leq 70^\circ$ with an increment of 5° would also give five sets of data. The effect from the connecting-to-rotating rod length ratio is plotted in Fig. 4c for $l_c/l_r = 0.5, 0.75, 1, 1.25$ and 1.5 . In deliberating the range of l_c/l_r ratio, we note that under the central value of $\theta = 60^\circ$, it is required that $l_c > 0.5l_r$ to prevent overlapping of the shurikens' pointed edges, hence $l_c/l_r = 0.5$ sets the lower bound, while there is no upper bound for l_c/l_r . Perusal to Eqs. (18) and (19) indicates that both expressions are simplified when $l_c/l_r = 1$. If this rod ratio is selected as the central value, then the choice of $0.5 \leq l_c/l_r \leq 1.5$ would be reasonable, and an increment of 0.25 would again give five sets of data.

The continuous effect of α_c/α_r , θ and l_c/l_r on the dimensionless effective CTE are displayed in Fig. 5. It shows that the negativity of the effective CTE upon cooling can be intensified (or the positivity of the effective CTE upon

heating can be reduced) by decreasing α_c/α_r or l_c/l_r or by increasing θ . It is of interest to note that while the material system fulfils the auxetikos criterion—as evident from the increasing thermal strain regardless of whether dT is positive or negative, and hence this system exhibits PTE under heating but reverses to NTE under cooling—the negativity of the CTE is of a greater extent in comparison to its positive counterpart. The existence of two curves, one each for heating and cooling, suggests that the effective CTE for the investigated material system herein is undefined when there is no change in temperature, for the CTE and its sign come into play only when one specifies the condition of temperature change—whether increasing or decreasing. In other words,

$$\lim_{dT \rightarrow 0^-} \alpha_x \neq \lim_{dT \rightarrow 0^+} \alpha_x \quad (20)$$

It is therefore unsurprising that Fig. 5 exhibits two sets of CTE—one for increasing temperature and one for decreasing temperature—although the CTE is non-existent for no change in temperature.

Thus far the characteristic of the interconnected shuriken model has been demonstrated for $\alpha_c/\alpha_r = 0, 0.25, 0.5, 0.75$ & 1 , $\theta = 50^\circ, 55^\circ, 60^\circ, 65^\circ$ & 70° , and $l_c/l_r = 0.5, 0.75, 1, 1.25$ & 1.5 , with central values at $\alpha_c/\alpha_r = 0.5$, $\theta = 60^\circ$ and $l_c/l_r = 1$. Outside the range of plotted results, the characteristics of the shuriken network can be approximated by means of extrapolated estimation. To obtain more accurate

Fig. 5 Variation of dimensionless effective CTE with reference to the **a** connecting-to-rotating rod CTE ratio, **b** rotating-to-connecting rod angles, and **c** connecting-to-rotating rod length ratio under heating and cooling

behavior of this network with different material and geometrical properties, one may perform calculations based on Eqs. (18) and (19) for heating and cooling, respectively, subjected to the following conditions to prevent the overlapping of neighboring shurikens or any other geometrical inconsistencies:

$$l_c \geq l_r \cos \theta \quad (21)$$

and

$$45^\circ < \theta = \sin^{-1} \left(\frac{l_s}{l_r} \right) < 90^\circ. \quad (22)$$

Finally, it is noted that the analysis is based on the assumption of straight lines with negligible width for the rods while the pin-joints are merely points. For practical consideration, a scaled-up model for a unit cell has been constructed to simulate the effects of cooling (both the rotating and connecting rods shorten) and heating (only the connecting rods are permitted to lengthen) so as to enable comparison between the theoretical and measured thermal strains. This is furnished in Fig. 6. It can be seen that the theoretical plots underestimate and overestimate the measured data points for cooling and heating, respectively. The discrepancies may well be attributed to the simplifications in the theoretical formulation wherein (a) the rods are of zero width and the pin joints are dimensionless points, and (b) the temperature change is infinitesimal.

4 Conclusions and recommendation

An auxetikos material, i.e. one that tends to increase, has been defined herein as a material system that exhibits positive strain whether the stimulus is of positive or negative value. By adopting the interconnected shuriken network, it has been shown that the material system expands based on the magnitude of the thermal change. This has been made possible by the presence of two sets of effective microstructure. One set of microstructure, whereby the rotating rod is redundant, takes effect upon heating wherein only the connecting rods expand. The other set of microstructure, in which the rotating and connecting rods are permitted to contract simultaneously, takes effect upon cooling. The capability of demonstrating two effective microstructures from just a single microstructure has been made possible through the implementation of a jamming or locking mechanism to render the rotating rods redundant under heating but functional under cooling. Results reveal that the effective CTE can be made more negative (under cooling) or less positive (under heating) by decreasing the α_c/α_r or l_c/l_r ratios, or by increasing the θ angle. It is herein proposed that a refined model be developed to take into consideration the finite change

Fig. 6 Comparison between theoretical plot (line) and measured data (points) for a scaled-up unit cell model with $\alpha_c/\alpha_r=0.5$, $\theta=63^\circ$ and $l_c/l_r=1$ at $\alpha_r=0.002 \text{ K}^{-1}$

in temperature and more realistic geometrical details be incorporated, such as rod width, so as to produce a more accurate predictive model. The capability for materials to exhibit similar response under opposing conditions—due to their ability to manifest opposing properties under opposing conditions—paves a way for engineers to design materials that are able to change their behavior to suit the environment.

Compliance with ethical standards

Conflict of interest The corresponding author states that there is no conflict of interest.

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